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GRAZING-INCIDENCE SPECTROMETER ON THE SSPX SPHEROMAK

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The Silver Flat Field Spectrometer (SFFS) is a high-resolution grazing-incidence diagnostic for magnetically confined plasmas. It covers the wavelength range of 25 - 450 Å with a resolution of $\Delta\lambda = 0.3$ Å FWHM. The SFFS employs a spherical 1200 lines/mm grating for flat-field focusing. The imaging is done using a back-illuminated Photometrics CCD camera allowing a bandwidth of around 200 Å per spectrum. The spectrometer has been used for atomic spectroscopy on electron beam ion traps and for plasma spectroscopy on magnetic confinement devices. The design of the SFFS and the spectrometer setup at the Sustained Spheromak Physics Experiment (SSPX) in Livermore will be presented.

I. INTRODUCTION

Plasma spectroscopy is an important diagnostic for laboratory plasmas studied in magnetic confinement fusion [1–3]. In these high-temperature plasmas, the extreme ultraviolet interval 25 - 400 Å of the electromagnetic spectrum is a regime where a multitude of prominent line radiation from plasma impurities fall. The EUV includes *L*-shell transitions from Be through Cl and *M*-shell transitions from mid-Z ions such as Ti, Fe, and Cu.

There has been a number of different spectrometers used for EUV diagnostics on magnetic fusion devices. In fact, extreme ultraviolet and vacuum ultraviolet (400 - 1200 Å) spectrometers are standard instruments on most magnetic fusion experiments [2]. One of the most frequently used spectrometer designs is the Survey Poor Resolution Extended Domain (SPRED) spectrometer, an instrument employing up to three different gratings with a total wavelength coverage from 100 Å up to 1700 Å with a resolution from 0.4 to 3 Å [4, 5]. The benefit of this instrument is the wide spectral coverage. However, the poor resolution can make line identifications an uncertain process. Another often used spectrometer is the SOXMOS design for the 5 - 340 Å range with $\Delta\lambda = 0.08$ Å using a 600 lines/mm grating [6]. Additional examples of EUV spectrometers on magnetic confinement devices include the Grazing Incidence Time Resolving Spectrometer (GRITS) that covers 15 - 360 Å with a wavelength resolution $\Delta\lambda = 0.7$ Å [7, 8]; the EUV spectrometers (10 - 130 Å and 50 - 500 Å) at the LHD stellarator with $\Delta\lambda = 0.08$ Å and 0.24 Å, respectively [9, 10]; and the X-ray and Extreme Ultraviolet Spectrometer (XEUS) at the NSTX tokamak, employing a 2400 lines/mm grating for the 6 - 65 Å range with $\Delta\lambda = 0.1$ Å [11].

Flat-field gratings, like the gratings used on the SPRED (toroidal grating), XEUS (spherical) and LHD spectrometers (spherical), are attractive dispersive elements since they both diffract and focus the radiation to a plane, allowing for the use of planar electronic detectors, such as charged-coupled device (CCD) cameras or multichannel plates (MCPs), enabling wider wavelength coverage without loss of spectral focus.

We here present a sister instrument to the XEUS spectrometer for use on high-temperature fusion plasmas. The spectrometer known as the Silver Flat Field Spectrometer (SFFS) is a high-resolution grazing-incidence instrument with a reflective grating. As several other instruments employed at magnetic fusion energy facilities [12], the spectrometer was designed at the Livermore EBIT facility [13], originally for use on electron beam ion traps. An earlier version of the spectrometer using the same grating is described in ref. [14]. The adaption we describe here has proven to be an important diagnostic for spheromak plasmas at the Sustained Spheromak Physics Experiment (SSPX) facility [15]. The SFFS spectrometer was recently moved to the NSTX tokamak in Princeton.

II. SPECTROMETER DESIGN

The Silver Spectrometer is a compact grazing-incidence spectrometer employing a spherical Hitachi grating (of the same type the XEUS and LHD spectrometers use) [16, 17] with an average groove density of 1200 lines/mm. The incident radiation impinges the grating around the blaze angle of 3.2°. The grating, originally intended for use on laser-produced plasmas, is mechanically ruled and aberration-corrected, designed to produce a flat focal field in the 50 - 250 Å wavelength range. The gold covered surface of 30 mm groove length and 50 mm groove distance has a radius of curvature of 5649 mm [16, 17]. The grating holder sits on a rotation table to enable matching of the incidence angle with the blaze angle, and is built to allow easy change of grating, e.g. the 2400 lines/mm XEUS grating.

Using a Klinger motorized linear stage the CCD detector can be translated to cover the spectral range 25 - 450 Å with a bandwidth of about 200 Å per image. The detector used at the SSPX spectrometer setup was a back-illuminated Photometrics CCD camera. The CCD array is made up of 1024 × 1024 pixels, each 25 μm in length, thus covering an area of 1 inch square. This large photon collection area enables the wide bandwidth

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of the spectrometer which, together with the high resolution, makes the SFFS a useful diagnostic. In order to reduce photon noise the CCD detector is cryogenically cooled with liquid nitrogen and operated at a temperature around -100 °C. The spectral background of the images thus mainly results from plasma bremsstrahlung, stray light from the spectrometer, read-out noise and high-energy cosmic rays impinging on the CCD. The CCD chip is uncoated and thus reflects optical photons, thereby preferentially selecting higher energy radiation such as ultraviolet and x-ray photons. Schematic views of the SFFS design are shown in Figure 1.

III. SPHEROMAK SPECTROSCOPY

The Silver Flat Field Spectrometer has been used for plasma diagnostics and atomic physics research on the SSPX spheromak. The SSPX facility at Lawrence Livermore National Laboratory was an experiment to investigate magnetic field buildup and energy confinement [18]. Instead of poloidal magnets surrounding the toroidal plasmas, as in a tokamak, the spheromaks were confined within a cylindrical flux conserver of diameter 1 m and height 0.5 m [19]. The flux conserver was made of tungsten-coated copper walls with a separation at the mid-plane for diagnostic access [20]. The plasma discharges lasted a few ms and achieved electron temperatures from a about 10 eV up to over 500 eV [18], and electron densities in the range 10^{13} - 10^{15} cm^{-3}. The SSPX diagnostics suite included a Thomson scattering system, a CO_2 laser interferometer system, magnetic probes and an ion doppler spectrometer [20], which together with the SFFS made the SSPX spheromak a well-diagnosed experiment. A layout of the SSPX diagnostics suite is shown in Figure 2.

With a field of view through the magnetic axis at the mid-plane of the toroidal spheromak plasmas, the SFFS sight line covered plasma regions of varying density and temperature. Due to the short SSPX discharges, the CCD camera recorded time-integrated images. Thus the spectra are both spatially and temporally integrated. The SFFS performed measurements during a multitude of SSPX experiments with different operating conditions, such as discharge lengths, electron temperatures and densities, and impurity concentrations.

From a diagnostics port of SSPX, the radiation entered the SFFS grating chamber roughly 2 m away through an imaging slit. Widths used were 34 and 100 μm. The low-conductivity slit together with other apertures in the beam-line reduced the stray light in the spectrometer and the gas load on the differentially pumped system. The pressure in SSPX during a discharge could rise to the mT-range, while the pressure of the SFFS grating chamber was held in the 10^{-7} Torr range by two turbomolecular pumps.

The SSPX plasmas had a multitude of line emission above 100 Å where O IV - VI were the dominating spectra in most discharges. Figure 3 shows a typical spectrum of the 100 - 200 Å range (SSPX shot 18360), where a 100 μm slit was used. The wavelength resolution varies across the grating, with a measured linewidth around 0.3 Å FWHM. The resolving power, $\lambda/\Delta\lambda$, for this shot is given for some of the lines in Table V. Spectra like 18360 are useful for collisional-radiative modeling verifications. Results of oxygen EUV modeling of SSPX plasmas are presented by Wilcox et al. in this issue (EUV spectroscopy of low-Z ion plasmas for fusion applications) [21].

The main purpose of the SFFS spectrometer at the SSPX spheromak was to identify impurity ions present in the device. We have successfully identified a multitude of impurity ions using spectral lines from He-like B IV at 60 Å up to W lines above 400 Å. Furthermore, the high instrumental resolution has permitted electron density and temperature measurements using line intensity ratios [22]. The Silver Flat Field Spectrometer has proven a very useful diagnostic for magnetic confinement plasmas.

IV. ACKNOWLEDGMENT

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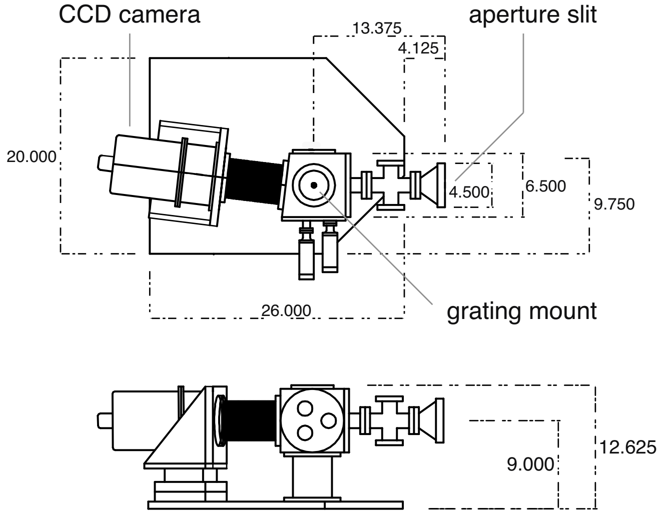

FIG. 1: SFFS outline. Top and side views. Dimensions in inches.

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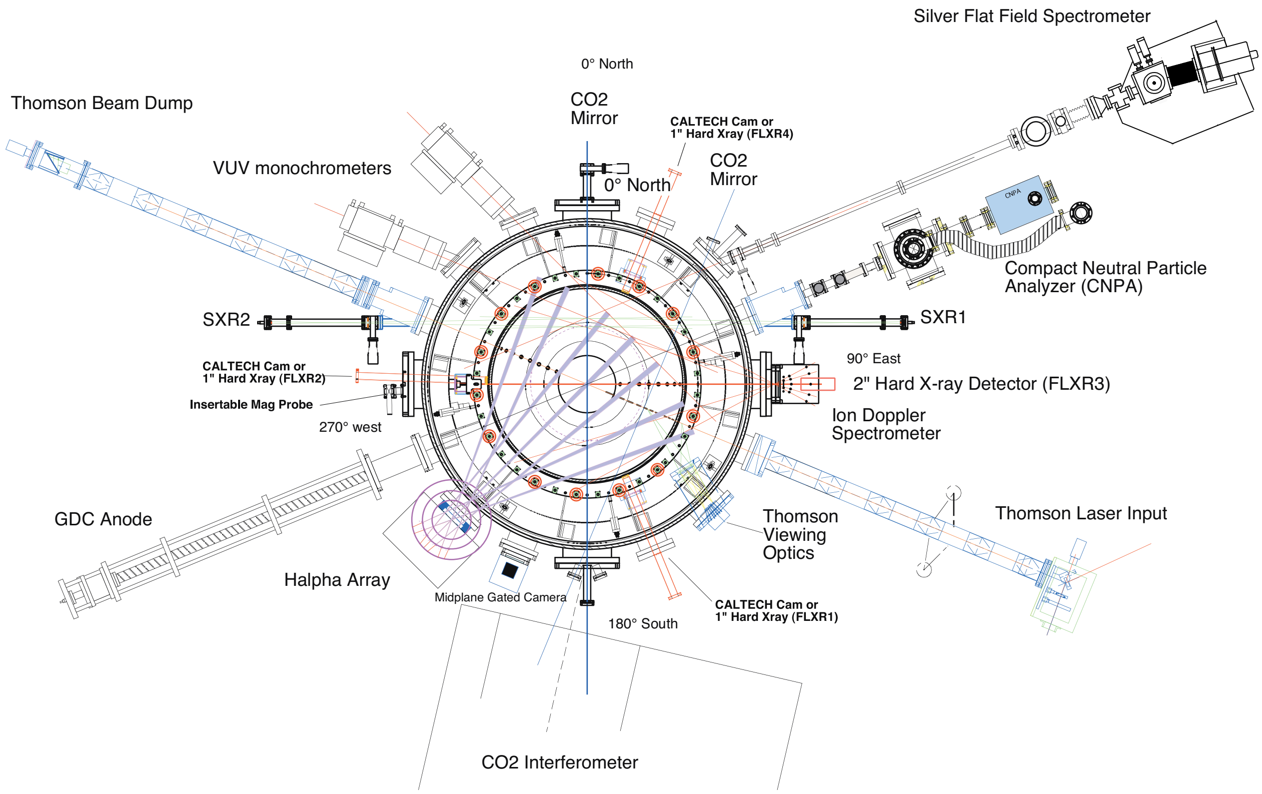

FIG. 2: SSPX diagnostics suite. The SFFS EUV spectrometer is shown in the upper right corner, approximately 2 m from the SSPX vacuum vessel. Blueprint courtesy of H. S. McLean.

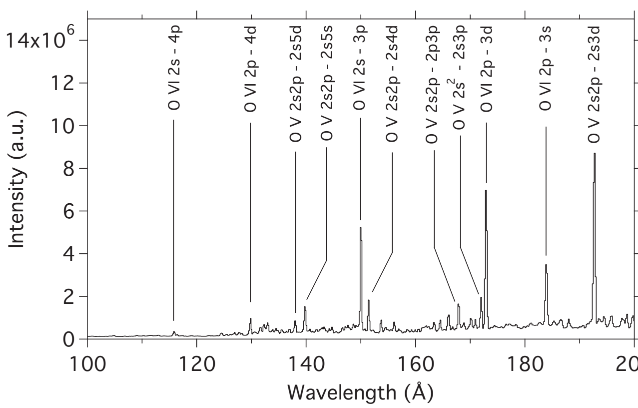

FIG. 3: SSPX shot 18360. SSPX emission above 100 Å is rich of line radiation, mainly from O IV - VI. Here are the some of the prominent oxygen lines labeled.

Spectrum	Transition	λ (Å)	$\Delta\lambda$ (Å)	$\lambda/\Delta\lambda$
O VI	2s - 4p	115.9	0.35	331
O VI	2p - 4d	129.9	0.28	464
O VI	2s - 3p	150.1	0.27	556
O V	$2s^2$ - 2s3p	172.2	0.30	574
O VI	2p - 3d	173.0	0.34	509
O V	2s2p - 2s3d	192.8	0.37	521

TABLE I: SFFS measured linewidths (FWHM) from SSPX shot 18360 using a 100 μm slit.